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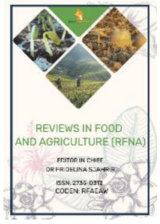

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RESEARCH ARTICLE

PRECISION AGRICULTURE: REVIEWING THE ADVANCEMENTS, TECHNOLOGIES, AND APPLICATIONS IN PRECISION AGRICULTURE FOR IMPROVED CROP PRODUCTIVITY AND RESOURCE MANAGEMENT

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ABSTRACT

Precision agriculture is a rapidly advancing field that combines advanced technologies and data analytics to improve crop productivity and resource management. This article reviews the advancements, technologies, and applications in precision agriculture. It explores the role of sensing technologies, such as remote sensing, ground-based sensors, and GPS/GIS applications, in data collection and analysis for informed decision-making. The article also examines the impact of variable rate technologies, including variable rate seeding, nutrient application, and irrigation, on optimizing input usage and improving crop performance. Furthermore, it discusses the integration of precision crop management techniques, such as remote sensing, artificial intelligence, and the Internet of Things (IoT), in enhancing farming practices. While precision agriculture offers significant benefits, challenges related to cost, accessibility, data management, and education need to be addressed. It is crucial to overcome these challenges to fully harness the potential of precision agriculture for sustainable and efficient food production. By acknowledging and addressing these challenges, farmers and stakeholders can work towards the widespread adoption of precision agriculture, leading to improved crop productivity, resource management, and environmental sustainability.

KEYWORDS

Remote sensing, Data Analytics, Robotics and Automation, Sustainability

1. INTRODUCTION

Imagine a future where each plant receives personalized care, optimizing its growth and minimizing resource waste. This is the promise of precision agriculture, a cutting-edge field that combines advanced technologies and data analytics to revolutionize crop productivity and resource management. Given the projected global population of nearly 10 billion by 2050, there is a pressing need to increase food production by approximately 50% compared to the levels achieved in 2013 (FAO, 2017). Unpredictable factors such as weather, soil conditions, pests, and changing crop conditions influence the dynamic nature of crop growth and its potential outcomes (Phupattanasilp and Tong, 2019). With the increasing global demand for sustainable food production and the need for efficient resource management, the development of Precision Agriculture has emerged as a promising solution. It was developed in the mid-1980s with an objective to enhance crop yield production and quality while simultaneously reducing operational expenses and minimizing environmental pollution (Chlingaryan, et. al., 2018) as well as enhancing the utilization of resources and minimize uncertainties associated with monitoring farm responses to spatial and temporal variations (Gorevlisi and Kekec, 2023). It encompasses a set of tools and technologies that enable farmers to make informed decisions for optimal resource management (Pierpaoli, et al., 2013). By focusing on the right actions, in the right location, at the right time, and in the right manner, Precision Agriculture strives to maximize efficiency and productivity in farming practices (Franca, et al., 2022). In the past decade, there has been a significant global increase in investments directed toward research and technological advancements in Precision Agriculture (Schellberg et al., 2008).

Precision agriculture refers to the implementation of hardware and software technologies that enable farmers to make informed and customized decisions about various agricultural activities, including planting, fertilizing, pest control, and harvesting (Dutta et al., 2021). Precision agriculture enhances resource allocation efficiency and overall farm management effectiveness (Liaghat and Balasundrsm, 2010). The allocation of energy resources in agricultural production varies significantly depending on the specific activities, production practices, and geographic locations involved, and the increasing reliance on imported energy sources for lubricants and nutrients raises concerns regarding its impact on the agricultural sector (Dhaya and Kanthavel, 2022). Precision Agriculture (PA) offers a paradigm shift towards a safe, sustainable approach, providing numerous benefits in terms of profitability, productivity, sustainability, crop quality, environmental protection, and rural economic development through efficient resource utilization and variability management (Liaghat and Balasundrsm, 2010). The success of precision agriculture lies in its ability to effectively utilize and analyze spatial and temporal data to assess, manage, and evaluate crop production, making it a fundamental principle for sustainable soil and crop management in the modern era (Pierce and Nowak, 1999).

In recent years, precision agriculture has witnessed remarkable advancements, with the application of artificial intelligence (AI) playing a pivotal role. AI has addressed challenges related to climate changes, population growth, employment, and food security while optimizing resource usage and improving crop productivity and quality (Talaviya et

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al., 2020). The advancement of precision agriculture is further supported by the application of blockchain technology, which enables transparent and trustworthy food supply chains, ensuring the traceability and provenance of agricultural products (Xiong et al., 2020). The integration of IoT-based technologies in agriculture, such as sensor networks and automated systems, has also significantly advanced precision agriculture practices. These technologies enable precise monitoring and control of environmental parameters, leading to improved crop quality and quantity in controlled environments like greenhouses. Additionally, IoT-enabled systems in hydroponics and vertical farming optimize resource consumption, enhance production efficiency, and reduce water usage compared to traditional farming methods, further contributing to the advancement of precision agriculture (Dhanaraju et al., 2022)

2. Sensing Technologies

Sensing technologies form a vital component of precision agriculture, facilitating data collection and analysis for informed decision-making in various aspects of crop management (Lee et al., 2010). The combination of cutting-edge sensing and actuating technologies, along with advancements in information and communication systems, creates the potential for significant progress in agricultural operations (Bochtis et al., 2014). There are various technologies encompassed within sensing technologies, including remote sensing techniques such as satellite imagery, aerial photography, and drones, as well as ground-based sensors like weather stations, soil moisture sensors, and nutrient sensors (Sishodia, et al., 2020). Furthermore, the utilization of global positioning system (GPS) and geographic information system (GIS) applications in precision agriculture further enhances data collection and analysis for informed decision-making in crop management as well as precise location tracking, mapping, and informed decision-making in crop management, optimizing resource utilization (Tagung et al., 2022; Tayari et al., 2015). Another study claimed that GPS and GIS technologies, when combined with other digital tools, play a crucial role in monitoring and optimizing agricultural practices, facilitating precision farming and sustainable food production (Ghosh and Kumpatla, 2022). The utilization of precision agriculture technologies, such as GPS, GIS, remote sensing, and active canopy crop sensors, including sensor-based N optimization algorithms, can optimize crop yields with minimal input usage, making them valuable tools for maximizing profitability and sustainability in developing countries (Farid et al., 2023). The use of remote sensors in precision agriculture involves both passive and active sensors. Passive sensors detect and record natural energy, typically reflected sunlight from the Earth's surface, while active sensors emit internal stimuli to collect data about the earth.

3. Variable Rate Technologies

Variable rate technologies (VRT) have revolutionized modern agriculture by enabling farmers to apply inputs such as fertilizers, seeds, pesticides, and irrigation water in a site-specific manner, taking into account the spatial variability of soil properties and crop needs. A survey conducted has resulted in a decrease in input use for fertilizer, lime, and seed inputs, leading to potential cost savings and improved resource efficiency by implementing variable rate technology in cotton production (Mooney et al., 2009). Additionally, for inputs such as irrigation and sprayer-applied substances, an increase in application has been reported, suggesting more precise and targeted use of these inputs, potentially enhancing crop performance and yield outcomes.

3.1 Variable Rate Seeding(VRS)

Variable rate seeding (VRS) is an accurate agricultural technology that adjusts seed quantities based on soil variability and other factors, leading to increased crop yields and improved farm profitability (Sarauskis, et al., 2022). VRS in corn production, compared to uniform rate seeding (URS), resulted in a potential economic benefit ranging from $0.15 to $12.83 per hectare, depending on the availability of information and technology adoption (Bullock et al., 1998). In addition, implementing variable rate seeding using the soybean VRS simulator resulted in potential profit improvements ranging from $5 to $57 per hectare compared to typical fixed seeding rate choices (Correndo et al., 2022). This demonstrates the potential economic benefits of adopting VRS in different crop production systems. The implementation of variable rate seeding (VRS) in agriculture has been limited globally, but with advancements in technology and easier implementation, there is increasing interest. The integration of high-precision satellite systems with Variable rate seeding (VRS) solutions empowers farmers to develop and implement customized strategies for precise seed placement, resulting in enhanced yield outcomes (Fulton, 2018).

3.2 Variable rate nutrient

Variable rate nutrient application (VRNA) is a precision agriculture technique that involves the application of varying fertilizer or manure rates across different sections of a field growing the same crop, according to a predetermined prescription. The practice of variable rate fertilizer management is expected to result in reduced fertilizer usage, increased or sustained yield, improved crop quality, and ultimately improved environmental quality (Teoh, et al., 2016). The advantage of variable rate nutrient application is the potential for improved profitability and environmental benefits. VRNA for phosphorus (P) can lead to long-term economic benefits by building up soil-test phosphorus, while VRNA for nitrogen (N) has the potential for economic and environmental benefits, although its adoption by producers is currently low. The use of real-time sensors for VRNA-N offers the potential to optimize nitrogen application based on crop needs, further enhancing the benefits of variable rate nutrient management (Grisso, et al., 2011).

3.3 Variable Rate Irrigation

Variable Rate Irrigation can be defined as the ability to apply water with varying depths across a field in a spatially specific manner, taking into account specific crop needs and other relevant conditions. VRI technology offers varying degrees of benefits and drawbacks depending on the specific field characteristics, with outcomes differing from field to field (Pokhrel, et al., 2018). Factors such as crop type, equipment lifespan, water cost, and pumping expenses play a crucial role in determining the return on investment associated with VRI implementation (Marek, et al., 2001). The states site specific Variable Rate Irrigation technology has the capacity to generate positive effects on crop water productivity, while also promoting water and energy conservation, and contributing to environmental sustainability (Envas et al., 2012). A study conducted in a vineyard resulted in a significant reduction of water use by 18% without compromising yield and product quality (Ortuani et al., 2019). The study also demonstrated that variable-rate irrigation in vine cultivation can effectively optimize water management and improve crop uniformity. In a study comparing variable rate irrigation (VRI) management to uniform rate irrigation (URI) management, it was demonstrated that VRI resulted in a 25% reduction in irrigation water usage and a 2.8% increase in soybean yield by (Sui and Yan, 2017). Despite the potential benefits of variable rate irrigation technology in improving water management and increasing crop yields, its implementation may encounter challenges such as insufficient leaching of salts, unintentional yield reductions in large fields, and the need to address the attitude and philosophy of the owner/operator (Oshaughnessy, et al., 2019).

4. Precision Crop Management

Precision Crop Management (PCM) is a data-driven approach in agriculture that optimizes profitability, sustainability, and environmental protection through the integration of diverse data sets and precision agriculture techniques. Various types of data, including yield distribution, soil characteristics, remote sensing, crop scouting observations, and weather information, can be collected at a site-specific level during the growing season to aid farm managers in optimizing crop management practices (Fountas, et al., 2015). It enables farmers to make informed decisions based on precise information, maximizing crop productivity while minimizing resource waste and environmental impacts (Jones and Barnes, 2000). The analysis and interpretation of collected data in precision agriculture enable the delineation of management zones, allowing for the optimization of crop management practices (Arno et al., 2009). Management zones formed based on data analysis and geostatistics in precision agriculture facilitate the implementation of variable rate application of inputs, enhancing crop management effectiveness (Taylor et al., 2007). GIS applications encompass land suitability assessment, water resource management, soil health and fertility management, biotic and abiotic damage assessment and intervention, crop monitoring and yield prediction, and biomass assessment (Ghosh and Kumpatla, 2022).

Remote sensing (RS) technology offers the capability to monitor the dynamic conditions of soil, plants, and the area under cultivation with high accuracy, achieving 95% accuracy in assessing the cultivated area and 90% accuracy in identifying single crop cultivation areas within a 10-day timeframe (Sahu, et al., 2019). The use of drones in agriculture has emerged as a valuable tool for inspecting large areas, implementing smart irrigation, and targeted fertilization (Gago et al., 2015). Infrared sensors in drones optimize crop monitoring and management, leading to improved crop conditions and increased yields, while also serving as valuable tools for power and pipeline inspections (Ahirwar et al., 2019). Drones equipped with infrared cameras enable the detection of irrigation needs and the spread of foliage diseases, leading to significant time and resource savings for agronomists while reducing the use of agrochemicals (Daponte et al., 2019). GIS-enabled cloud technology serves as a decision support system for soil fertility management, utilizing soil test and crop response data to provide accurate fertilizer recommendations. This enables farmers to optimize fertilizer usage and maximize crop yield (Leena, et al., 2016) Furthermore, Remote sensing enables precise identification and mapping of weed patches within fields, allowing targeted herbicide applications and minimizing environmental contamination while optimizing weed control (Jr et al., 2003).

The application of GPS guidance in sugarcane farming enables the implementation of controlled traffic systems with wider row spacing and permanent cropping beds, which can help mitigate yield decline caused by wet conditions and soil compaction, leading to potential yield increases (Palaniswani, et al., 2011). Ground-based or near-range sensors, such as cameras, spectrometers, fluorometers, and distance sensors, have the potential to be employed for the detection and quantification of weed presence and infestation levels in precision agriculture (PA) applications(Peteinators et al., 2013). Moreover, these advanced farming techniques contribute to increased crop productivity and improved quality by precisely identifying and addressing issues such as water deficiency, nutrient stress, and diseases. The use of thermal indices derived from infrared radiation has been investigated for precise water management in agriculture. These methods allow for monitoring plant water status, estimating evapotranspiration rates, and optimizing irrigation timing and quantities based on crop water requirements (Jr et al., 2003). CIR (Color Infrared) photography from remote sensing technology is used to identify areas affected by specific diseases, estimate yield losses caused by disease in crops, and detect diseases that hinder water flow in plants and thermal infrared (TIR) imaging is used for early detection of diseases (Jr et al., 2003). These applications enable farmers to take proactive measures in disease management.

In addition, Artificial Intelligence(AI) has also emerged as a powerful tool in crop management. The use of AI-powered chatbots assists farmers in receiving real-time answers, advice, and recommendations on crop diseases, pest control, and irrigation practices by analyzing queries, accessing relevant data, and delivering tailored solutions. This AI-enabled support system enhances farmer knowledge, decision-making, and efficiency, minimizing losses and reducing workloads in farming (Talaviya et al., 2020). Moreover, the IoT technology, with its sensors and instruments, enables farmers to remotely monitor plants and animals, assess weather conditions, and anticipate production levels. For example, through IoT-enabled systems, farmers can effectively manage water resources by monitoring and controlling the flow amount, assessing crops' water requirements, and optimizing the timing of water supply, leading to significant water savings and improved crop productivity in precision agriculture (Dhanaraju et al., 2022).

5. Robotics and Automation in Precision Agriculture

In precision agriculture, automation and robotics have emerged as a central framework, extensively researched and applied in various agricultural operations such as planting, inspection, spraying, and harvesting, with a focus on minimizing environmental impact and maximizing agricultural productivity (Mahmud et al., 2020). Agricultural robots have expanded in categories and diversified in application scenarios, including field robots, fruit and vegetable robots, and animal husbandry robots, to meet the practical needs of labor-saving and efficient agricultural production (Cheng, et al., 2022). Field robots in agriculture are autonomous, mechatronic devices that primarily utilize wheels for locomotion and are designed to perform various tasks such as tilling, sowing, plant protection, data gathering, and harvest operations, with drones being primarily used for pesticide spraying (Lowenberg-DeBoer et al., 2020). Seeding robots, as part of field robot systems, have been developed to precisely sow seeds in designated positions, contributing to enhanced accuracy, time efficiency, and cost savings for farmers (Cheng et al., 2022). Transplanting robots offer the benefit of improved accuracy and stability during the transplanting process, ensuring successful transplantation with a high success rate even at accelerated speeds; 95.3% even at an acceleration of 30 m/s^{2} (Yang, et al., 2020). In harvesting fields, a cost-effective two-wheeled robot equipped with a spraying mechanism and wireless control for pesticide and fertilizer application has been developed (Ghafar et al., 2023). The robot also utilizes cameras to monitor crop growth conditions, and health factors, and detect pests in the field. By utilizing robots for fertilizer spraying, farmers have the potential to reduce pesticide usage by up to 80%, while also benefitting from the robots' ability to navigate around obstacles such as trees, rocks, and lakes, thereby enabling more efficient cultivation across fields (Sachithra and Subhashini, 2023). Automation and robotics in precision agriculture have revolutionized farming operations, offering enhanced accuracy, efficiency, and cost savings while minimizing environmental impact, with the potential to reduce pesticide usage by up to 80% and navigate challenging terrain for more efficient cultivation.

6. Conclusion

In conclusion, precision agriculture is a promising solution for improving crop productivity and resource management. By leveraging advanced technologies like sensing, variable rate applications, and automation, precision agriculture optimizes farming practices. It enables informed decision-making, reduces resource waste, and enhances sustainability. However, challenges remain in terms of cost, accessibility, data management, and education. With further research and collaboration, precision agriculture has the potential to revolutionize farming and meet global food demand while minimizing environmental impact.

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